SEYMOUR

Water Hammer in Pipes

Civil Engineering

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WATER HAMMER IN PIPES

BY

BUDD WILLARD SEYMOUR

THESIS

FOR

DEGREE OF BACHELOR OF SCIENCE

IN

CIVIL ENGINEERING

COLLEGE OF ENGINEERING

UNIVERSITY OF ILLINOIS

PRESENTED JUNE 1903

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June 1, 1903

This is to certify that the thesis prepared under the supervision of Professor Talbot by BUDD WILLARD SEYMOUR, entitled WATER HAMMER IN PIPES, is approved by me as fulfilling this part of the requirements for the Degree of Bachelor of Science in Civil Engineering.

Ira O Baker

Head of Department of Civil Engineering

61525

Water Hammer in Pipes

The pressure developed when the velocity of water flowing in a pipe is suddenly arrested by the closing of a valve, has long received the attention of hydraulic engineers. Several series of experiments on water hammer in pipes and many analytical discussions of the phenomenon have been made, which have added materially to our knowledge of the subject.

It has not been the intention of the writer to make an elaborate discussion of the subject, but rather to collect available data and to test their accuracy by experiments, to make such further investigations as the facilities at hand afford, and to state the results and conclusions reached.

UIUC

Existing Literature.

There is comparatively little literature on the subject of water hammer. Much of what has been written is theoretical and is based upon many assumptions or involves erroneous principles. Some of the discussions which seem to be along the right line will be reviewed for merits. In general only conclusions reached will be stated and no attempt will be made to go into detail.

A thesis on the subject of water hammer in pipes was written by Mr Elmer Hewitt, Lehigh U. Bethlehem, 1899. He made numerous experiments under different conditions, varying the length of the pipe, the velocity of the water flowing in the pipe, and the rapidity of closing the valve. From his experiments he arrives at the following conclusions:—

1— The pressure varies as the speed of

closing the valve.

2- The pressure varies as the velocity of the water flowing in the pipe varies.

3- The pressure along the pipe line not decrease in the distance from the valve increases but varies as the square root of the distance.

Much credit should be given to Mr. Smith for the results obtained, since they are based upon numerous experiments and since the conclusions are drawn the best made. His experimental work may be relied upon that the conclusions may be said to be sound.

See Turneaure and Russell's "Public Water Supplies" page 243 in the formula.

$P = \frac{V}{V}\sqrt{\frac{EW}{F}} = 67V$ where P equals the pressure in pounds per square inch,

V = velocity of water in the pipe,

V = velocity of sound in water = 4,900 ft.

E = Modulus of elasticity of water = 300,000.

The above formula was carefully stated, no attempt being made to derive it.

In the Transactions of the American Society of Civil Engineers volume 39 page 1, Mr. L. F. Fritzell gives a discussion of the theory of water hammer, he derives an equation for the velocity of the sound through the water in the pipe, it is $V = \frac{L}{t} = \sqrt{144 \frac{g}{W} \times \frac{m M T}{2r(m+M)T}}$ where $g = 32.2$, $W = 62.5$ m = modulus of elasticity of water, M = the modulus of elasticity of the material of the pipe, T = thickness of the pipe in inches r = radius of the pipe in feet. Assuming a 60-inch steel pipe ½ inch thick he finds $V = 4272$ feet per second. Neglecting the distention of the pipe $V = \sqrt{144 \frac{g m}{W}}$ = 4672 feet per second, which is approximately the velocity of sound in water. His formula for pressure is $P = \frac{V}{V} \cdot \frac{m}{1 + \frac{2r}{T} \times \frac{m}{M}}$ V = the velocity of sound in water.

He states but does not prove that the pressure is limited by the sudden stopping of the water in a pipe of indefinite length independent of the length of the column of water, when the valve is closed instantaneously;

and that the valve may be said to be closed instantaneously when the time of closing is less than the time it takes the impulse to travel from the valve to the free end of the pipe and return to the valve. In the volume above referred to, page 9, Mr T. A. Noble gives a discussion. He assumes that the pressure along the pipe varies inversely as the distance from the valve. This is a wrong assumption, as all experiments show.

In the Engineering News of March 24, 1898, volume 39, page 186 there is a summary of Mr. Samuel McCoy's thesis on water hammer, at Dartmouth College. His conclusions were based upon several experiments and are as follows:

1 – The force of the ram varies as the velocity of the water flowing in the pipe.

2 – The force of the ram varies as the speed of closing the valve.

In the Engineering News of Aug. 2, 1900.

volume 44 page 80 there is a summary of the results obtained from the experiments of Prof. N. Zukowsky of the Imperial University of Moscow. His results were derived from very extensive experiments with different sizes and lengths of pipe. Briefly stated the results are:

1- The hydraulic shock is propagated along the pipe with a constant velocity, the magnitude of which does not depend upon the pressure of the main. This velocity depends upon the material of the pipe and the ratio of the thickness of its walls to its diameter.

2- The appearance of periodic oscillations in the pressure in the water-pipe is completely explained by the reflection of the shock-wave at the end of the pipe.

3 The magnitude of the shock is proportional to the velocity of the water and to the velocity of the wave propagation.

4- The motion of the water as a body has no noticeable influence on the shock, the latter is determined only by the last velocity.

Theory of Water Hammer

The theory of water hammer as given by Prof. F. N. Talbot is here presented. When water flowing in a pipe is suddenly arrested by the closing of a valve, the water near the valve is compressed a certain amount, while at the pipe end there is no compression. Neglecting the distention of the pipe for the present; let dx equal the length of a column of water whose cross-section is 1 square foot, let P equal the pressure at the valve on 1 sq. inch generated by the sudden stoppage of the water, then 144 P equals the pressure on 1 square foot. If w equals the weight of a cubic foot of water, w dx equals the weight of a column of water 1 square foot cross-section and dx long. The energy in this water flowing with a velocity V, is equal to $\frac{1}{2} M V^2$. Since $M = \frac{w dx}{g}$, this becomes $\frac{1}{2} \frac{w dx}{g} V^2$. Let λ equal the amount this dx length of water is compressed at the

value. Since λ is proportional to the unit stress, $\lambda = \frac{Sl}{E}$, where $S = P$, l = length of the column of water = dx and E = the modulus of elasticity of water. A value of 300 000 is here used for E, what error there is in this will not affect the result appreciably. The product is in foot pounds if dx is expressed in feet. The work done is equal to the average pressure multiplied by the distance moved through. The average pressure equals $\frac{144P}{2}$ since the pressure increases from 0 to 144 P. Then the work done is equal to $\frac{144P}{2}\lambda$ or $\frac{144P}{2} \times \frac{Pdx}{E}$. The work done is equal to the energy in the water $\therefore \frac{144P}{2} \times \frac{Pdx}{E} = \frac{1}{2}\frac{W}{g}dx V^2$

$P^2 = \frac{WE}{144g} V^2$, $P = \sqrt{\frac{WE}{144g}}\, V$. Substituting for W, E and g their numerical values we have $P = 63.6\, V$. This is the value for the pressure at the valve generated by the sudden stoppage of the water, when the elasticity of the metal is not taken account of.

Considering the elasticity of the metal

in the pipe we have the deformation λ_2 of the pipe $= \frac{\pi d}{E'} S$ also $Pd = 2tS$, $S = \frac{Pd}{2t}$, where P = the pressure per unit area, d = the diameter of the pipe, t = the thickness of the pipe and S = the tensile stress of the metal in the pipe in pounds per square inch, E' = the modulus of elasticity of the metal = 30 000 000. Then $\lambda_2 = \frac{\pi d^2 P}{2tE'}$. For a length dx the total lateral pressure F_2 in the pipe $= \frac{Pd}{2} dx$. Work done in stretching the pipe $= \frac{1}{2} F_2 \lambda_2 = \frac{1}{2} \cdot \frac{Pd}{2} dx \cdot \frac{\pi d^2 P}{2tE'} = \frac{1}{8} \cdot \frac{\pi P^2 d^3}{tE'} dx$. Work done in compressing the water $= \frac{1}{2} F_1 \lambda_1 = \frac{1}{2} \cdot \frac{\pi d^2}{4} \cdot \frac{P}{E} dx = \frac{1}{8} \frac{\pi P^2 d^2}{E} dx$. Energy of the water $= \frac{1}{2} \cdot \frac{w}{g} \cdot \frac{\pi d^2}{4} dx \cdot V^2$. Equating energy to work done we have $\frac{1}{8} \frac{w}{g} \pi d^2 dx V^2 = \frac{1}{8} \frac{\pi P^2 d^3}{E} dx + \frac{1}{8} \frac{\pi d^2 P^2}{tE'} dx$. Reducing,

$$\frac{wE}{g} V^2 = 1 + \frac{Ed}{E't} P^2, \quad P^2 = \frac{1}{1 + \frac{Ed}{E't}} \cdot \frac{wE}{g} V^2,$$

$$P = \frac{1}{\sqrt{1 + \frac{Ed}{E't}}} \cdot \sqrt{\frac{wE}{g}} V.$$ pressure per unit area expressed in homogeneous units. Expressing (P) in pounds per square inch and V in feet per second, this reduces to $P = \frac{1}{\sqrt{1 + \frac{Ed}{E't}}} \cdot \sqrt{\frac{wE}{144g}} V$. This formula is in the same form as the one where the elasticity of the pipe was neglected.

the only difference is in the constant $\frac{1}{\sqrt{1+\frac{Ed}{E't}}}$ depending upon the size and thickness of the pipe. For the size of pipe used by the writer $d = 2.06$ inches, $t = .154$ inches Then by the formula $P = \frac{1}{\sqrt{1+\frac{2}{15}}} \cdot 63.6\ V$, or

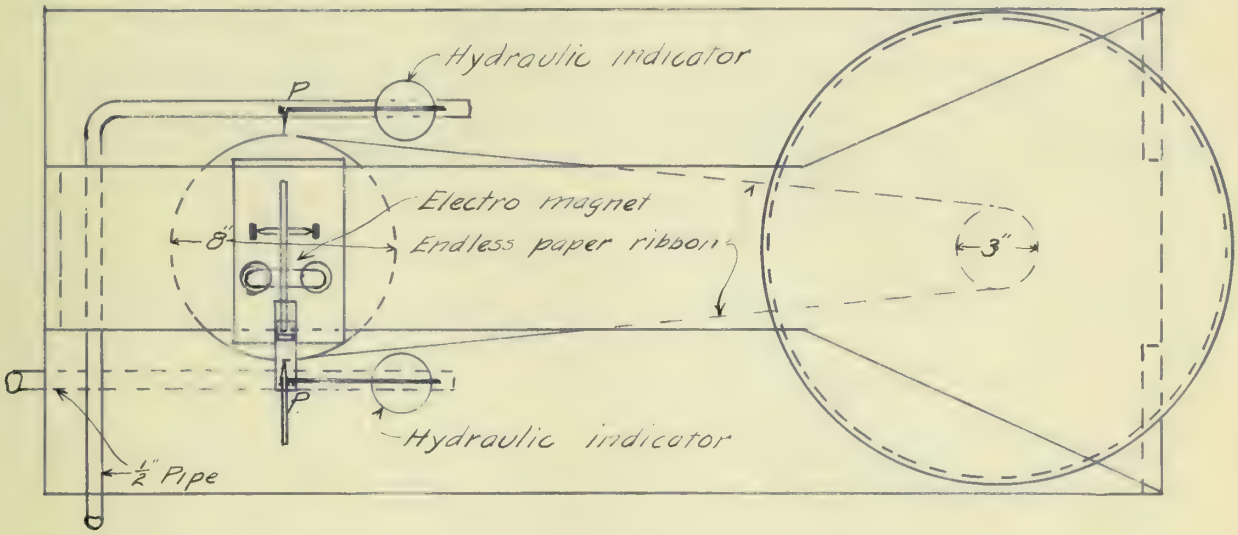
$P = 59.7\ V$.

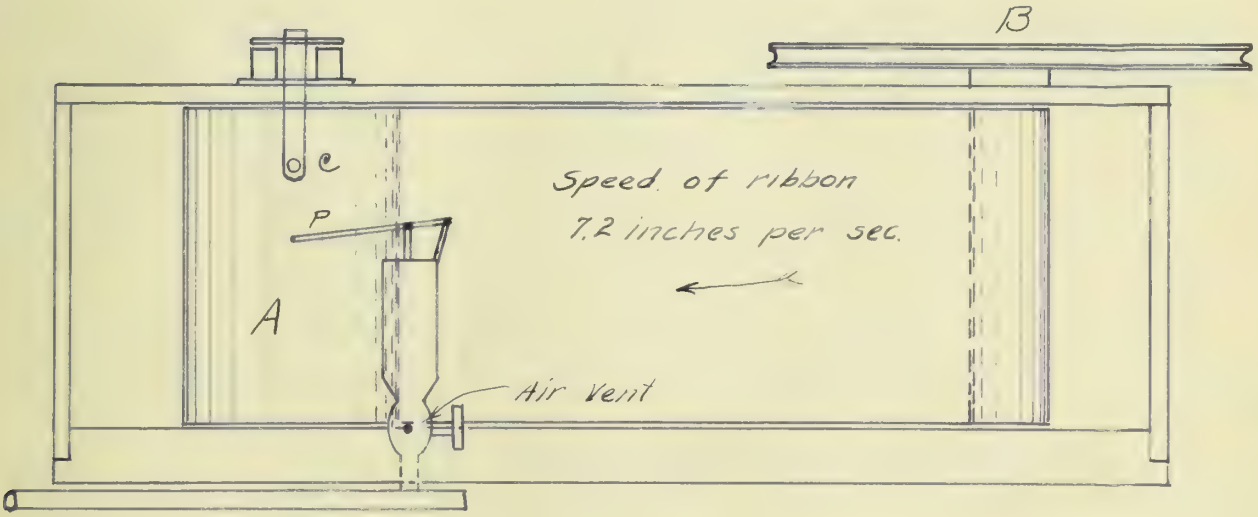
By the same reasoning as above, when the elasticity of the pipe is taken into account the velocity of the impulse was found to be $\frac{1}{\sqrt{1+\frac{Ed}{E't}}} \cdot V'$ where V' equals the velocity of sound in water. For the temperature of the water, size and thickness of the pipe used by the writer, this formula gives the velocity of the impulse $V = \frac{1}{\sqrt{1+\frac{2}{15}}} \times 4700 = 4409$ ft. per sec.

Apparatus.

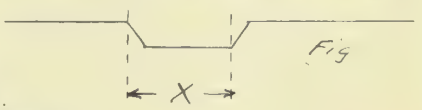
In the experimental work made by the writer as hereafter described, the water was taken from a stand-pipe 60 feet high. The velocity of the water flowing through the pipe system was regulated by a valve at the stand-pipe. This velocity was determined by running the water into a tank for 60 seconds and weighing it; knowing the area of the pipe the velocity could easily be found by the formula, $V = \frac{Q}{A}$. The pipe used in these experiments had a diameter of $2\frac{3}{32}$ inches. A quick-closing lever valve of a special, new pattern was used at the outlet for quick closing. Several air vents were provided along the pipe. The amount of the pressure was measured by two Crosby explosive indicators, using the 480 spring except in the four velocities in which a 200 spring was used. The sketch on page 13 shows the arrangement

SKETCH
SHOWING
RECORDING DEVICE





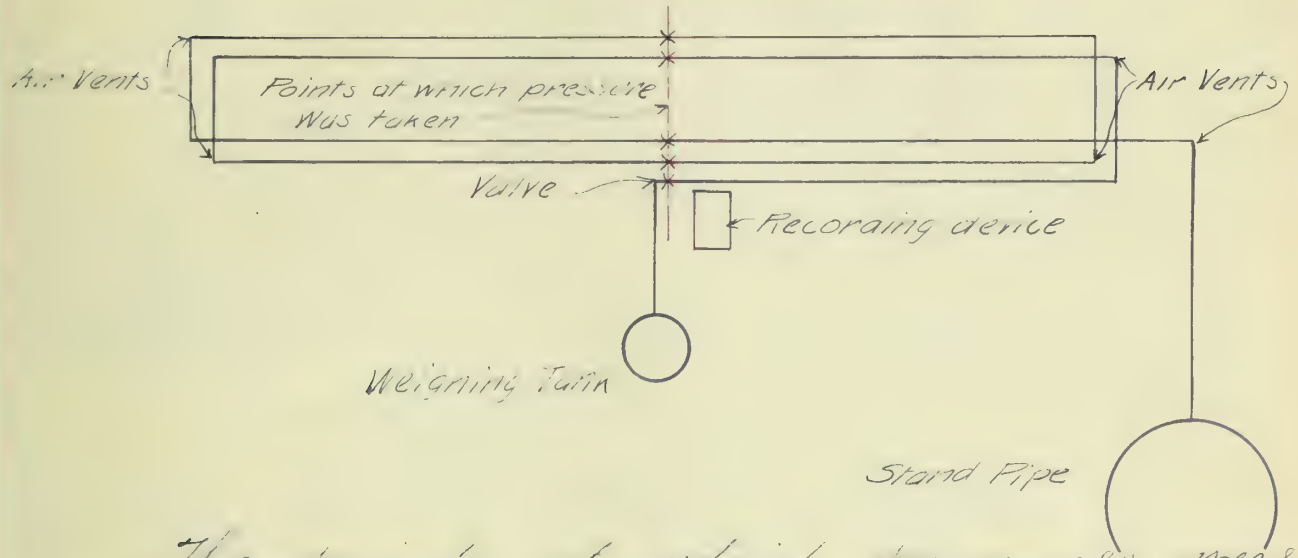
and general plan of the recording device. The pencils (P) record the pressure on an endless paper ribbon running over an 8-inch drum (A) at a speed of 7.2 inches per second, which was driven by a belt running over an 18 inch pulley (B) to an electric motor known to run at a uniform speed. The time of closing the valve was measured by a pencil (C) marking on the moving ribbon. The pencil was attached to an electro-magnet in such a way that when the valve started to open an electric connection was made and the magnet 'caught' the pencil down; when the valve was fully closed the connection was broken and the magnet was drawn back by means of a spring thus raising the pencil. An ordinary telegraph sounder was used for a magnet. The line made by the pencil at valve-closure was like figure.



Fig

The distance x is the time in which the valve is closed.

Layout of the Pipe



The points at which pressures were taken were 50 feet apart. The connection between the 2 in. pipe and the indicator was by a ¾ inch pipe about 50 feet long arranged with swing joints so that the air in the pipe would not be communicated to the indicators.

Pressure Along the Pipe

The experimental values found for the pressure along the pipe are shown in plates 1 and 2. It will be noticed that the pressure does not decrease as the distance from the inlet increases, but varies nearly as the square root of the distance, or the lengths of pipe used. The values were plotted upon log-log paper, and it was found that a straight line could not be made to pass through the points, showing that the function is not an exponential curve. It was also found that a straight line approximating a set of experimental values, or a single curve, did not have the same origin as that approximating the values for another set, showing that a single empirical function will not cover all experiments.

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PRESSURE ALONG THE PIPE

300 FT. 2 IN. PIPE

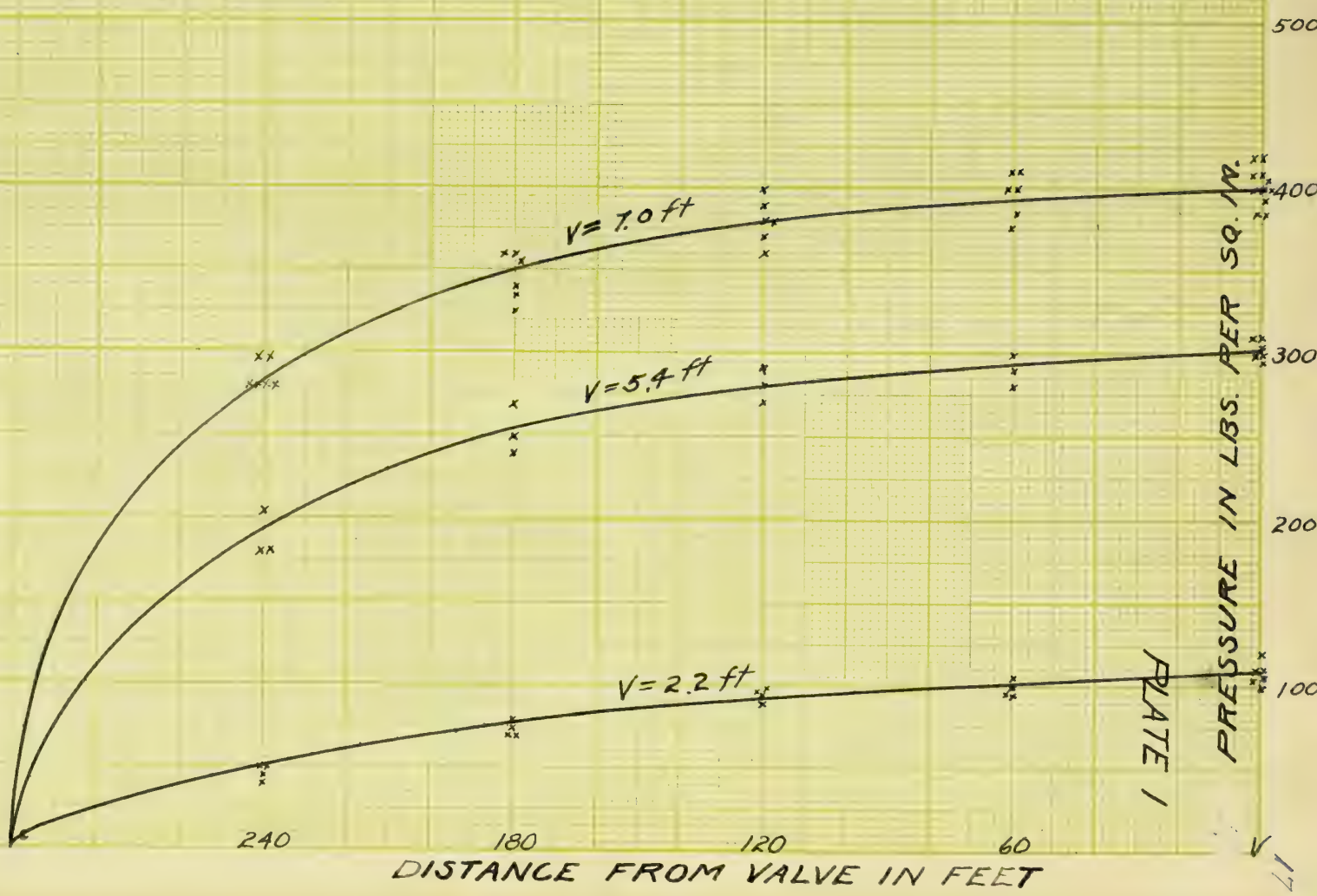

PLATE I

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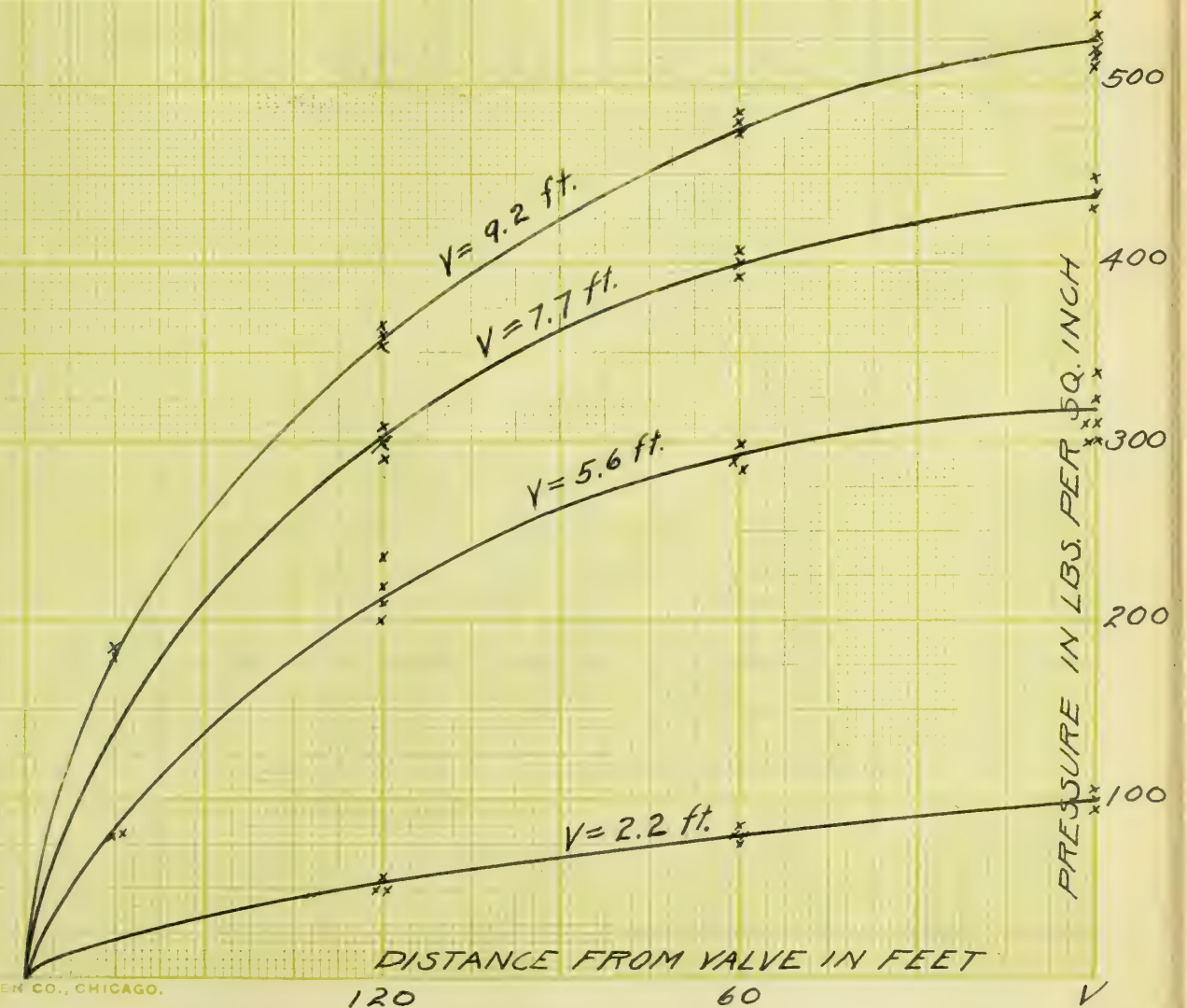
PLATE 2

PRESSURE-ALONG-PIPE

180 FT. 2 INCH PIPE



EUGENE DIETZGEN CO., CHICAGO.

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Pressure at the end.

Numerous experiments were taken to determine the pressure at the end and the ratio between this pressure and the velocity of the water flowing in the pipe. The mean of the observed pressures was assumed as the pressure in the following table.

Relation between pressure and velocity

300 Ft. Pipe

Velocity in feet per sec.	Pressure in lbs. per sq. in.	$\frac{P}{V}$
7.0	400	57
5.4	304	56
2.2	110	50

180 Ft. Pipe

Velocity in feet per sec.	Pressure in lbs. per sq. in.	$\frac{P}{V}$
9.2	525	57
7.7	440	57
5.6	320	57
2.2	110	50

It will be noticed that, as shown in the table, we would be

than the theory requires when we neglect the distention of the pipe, but taking the distention of the pipe into account the results are only a very little less. This difference may be caused by the play of the valve. Considering this the results of the experiments agree with the theory.

Velocity of the Impulse

When the valve is closed a pressure is produced. This pressure is not felt throughout the whole length of the pipe at the same instant, but an impulse is transmitted throughout the length of the pipe, traveling back from the valve at a certain velocity. This was found by placing indicators at points along the pipe 60 feet apart. The pipe was so arranged that these points were assembled at one place for convenience in recording the records of the indicators on one drum. Having the records of the indicators on the same drum and knowing the distance between the indicator points, the time between the pulsations at any two points along the pipe could be determined by measuring the distance between the pulsations as recorded; then the

difference between this distance and the constant distance between the pencil points, would be the distance the ribbon travels in the time between the pulsations. Since the ribbon travels at a uniform speed the time between the pulsations was easily determined. This time was the time it took the impulse to travel the distance in the pipe between the indicators. It was found to be constant between all indicators along the pipe. The results of several experiments gave a velocity of 4600 feet per second for the impulse. It will be noted in the diagrams on plates 3 and 4 that the pulsations with low velocities do not occur as soon after valve closure as do those with high velocities. No explanation can here be given for this.

PLATE 3

DIAGRAM

SHOWING VELOCITY OF THE IMPULSE ALONG THE PIPE SYSTEM

300 FT. 2-INCH PIPE

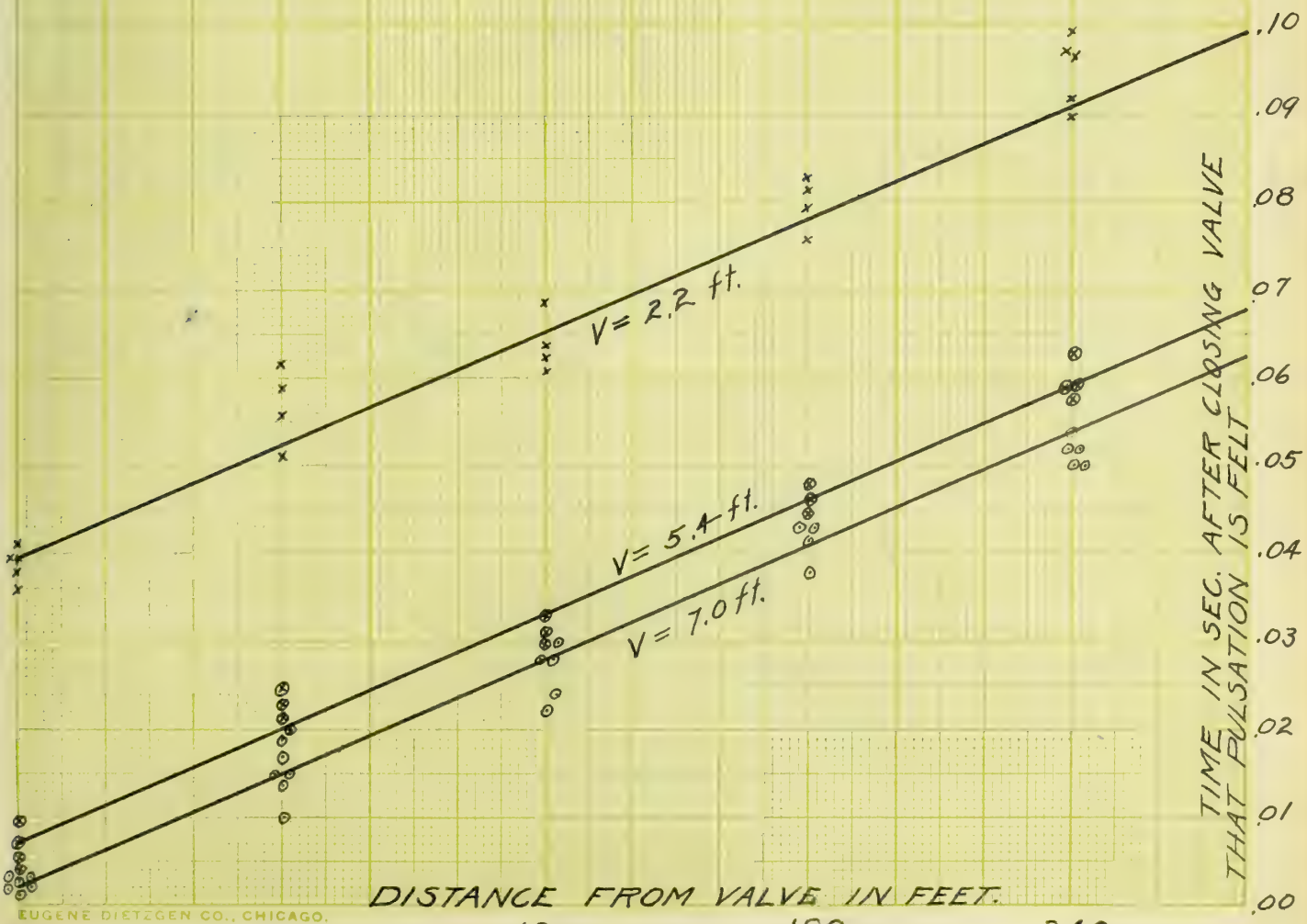

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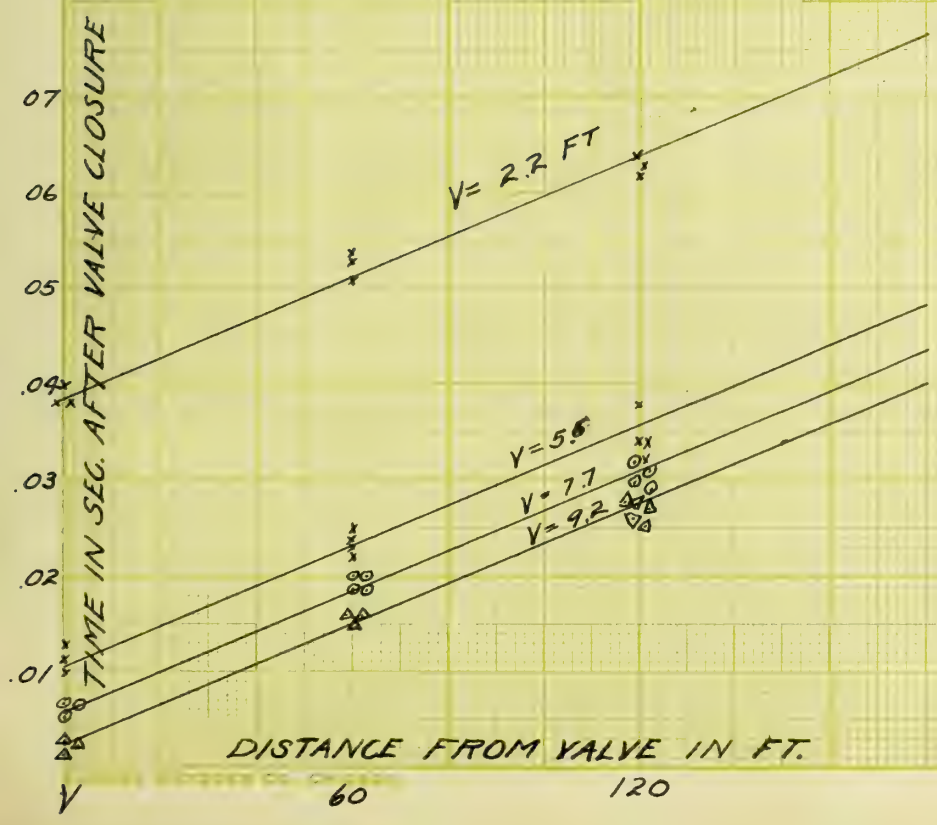
PLATE 4

DIAGRAM
SHOWING VELOCITY OF THE IMPULSE
ALONG THE PIPE SYSTEM
180 FT. 2-IN. PIPE

VELOCITY = 4600 FT. PER SEC.



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Duration of Compression

When the valve is closed the water flowing in the pipe is suddenly arrested. The water was flowing with a certain velocity and work was done in stopping it. When the valve is closed, the water will continue to flow in at the free end. The water in the pipe will be compressed at the valve first and finally throughout the pipe. When the compression reaches the free end, the water ceases to flow in. The compression is then relieved, first at the free end and last at the valve. Since this compression takes at a uniform velocity (4600 feet per second, same as the impulse wave before described), the time that the water will remain compressed at the valve will be the time that it takes the impulse to travel from the valve to the free end and return to the valve again.

The diagrams on plate 5 and 6 show the duration of the compression at any point along the pipe. These diagrams are the results of several experiments on both 300 feet and 180 feet of pipe and at several velocities.

DIAGRAM
SHOWING DURATION OF COMPRESSION
AT POINTS ALONG THE PIPE
300 FT. OF 2 INCH PIPE

VELOCITIES

x = 7 FT PER SEC.

⊙ = 6.8 " " "

Δ = 5.4 " " "

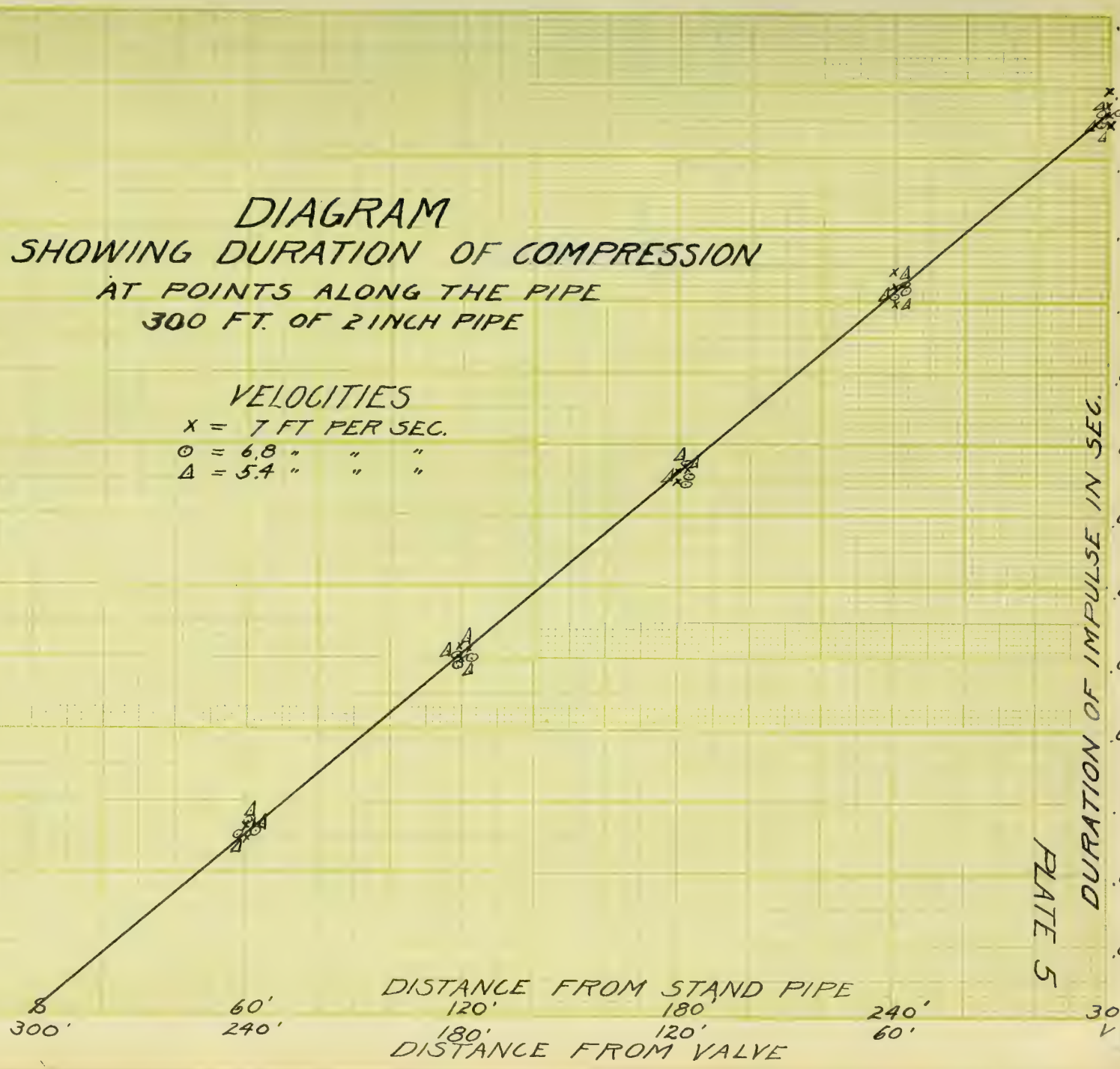

PLATE 5

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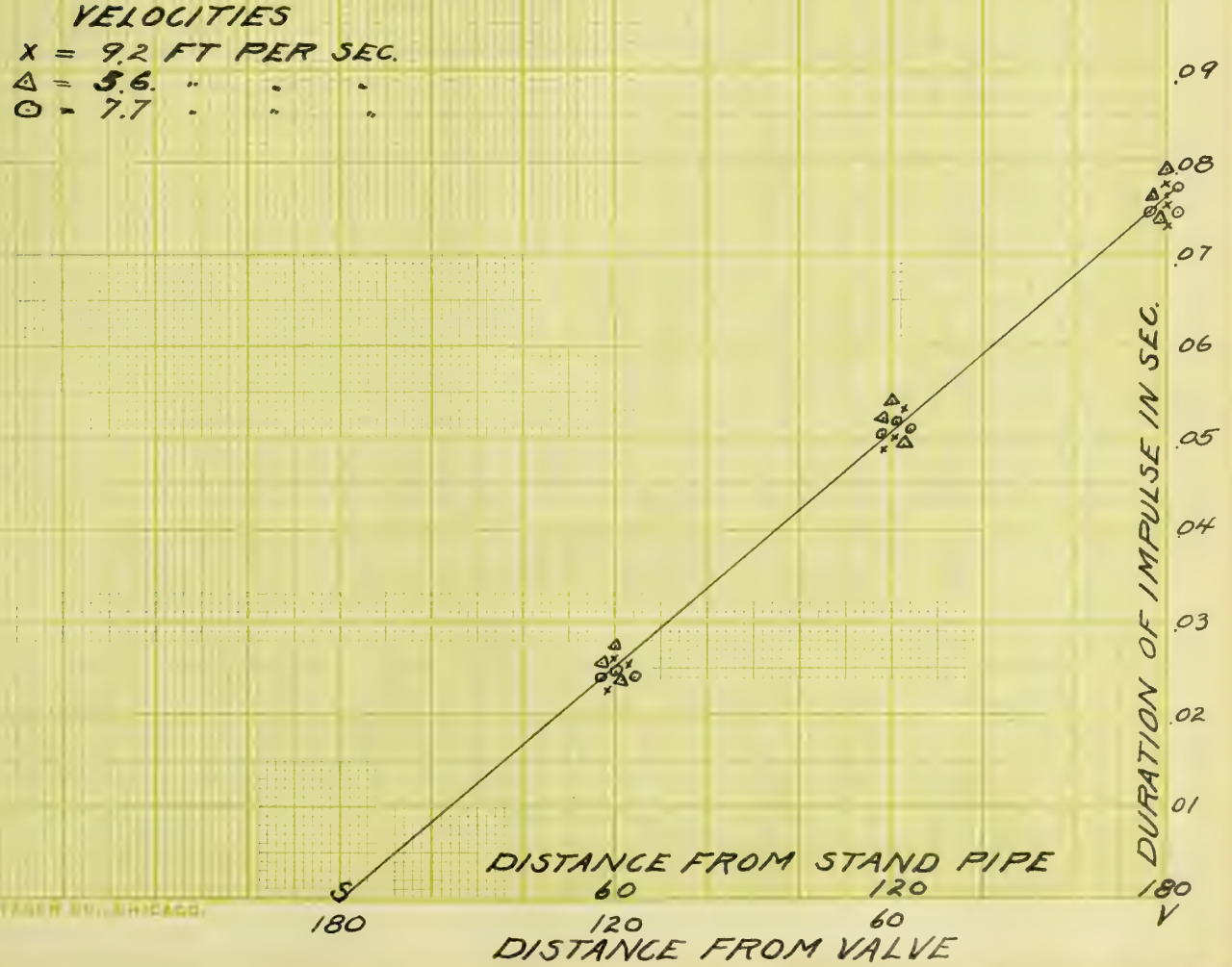
PLATE 6

DIAGRAM
SHOWING DURATION OF COMPRESSION
AT POINTS ALONG THE PIPE
180 FT. OF 2 INCH PIPE



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Relation Between Successive Pulsations

In all the experiments made except those with low velocities it was noticed that the pressure would come in pulsations, the time between these pulsations decreasing as the number of the pulsations increased. In some cases 7 or 8 pulsations were felt before they would finally die out. The time between any two successive pulsations was much longer than the time it took the impulse to travel from the valve to the free end and return again. Corresponding pulsations were the same time apart at any point along the pipe. The following tables are presented for comparison of pulsations and pressures, and the time between any two pulsations.

Tables showing consecutive pulsations corresponding pressures & time between pulsations

300 ft Pipe V = 7.0 ft

Pulsations	Pressures in lbs. per sq."	Time between Pulsations in seconds
1	430	
		1.29
2	288	
		.96
3	144	
		.74
4	80	
		.64
5	20	
		.62
6	10	

300 ft Pipe V = 5.4 ft.

Pulsations	Pressures lbs. per sq. in.	Time between Pulsations in seconds
1	300	
		.96
2	192	
		.72
3	90	
		.63
4	40	
		.58
5	15	

180 ft Pipe, V = 9.2 ft.

Pulsations	Pressures lbs. per sq. in.	Time between Pulsations in seconds
1	540	
		.97
2	250	
		.75
3	175	
		.66
4	75	

180 ft. Pipe V = 7.7 ft.

Pulsations	Pressures lbs. per sq. in.	Time between Pulsations in seconds
1	440	.79
2	240	.66
3	125	.57
4	75	.50
5	25	

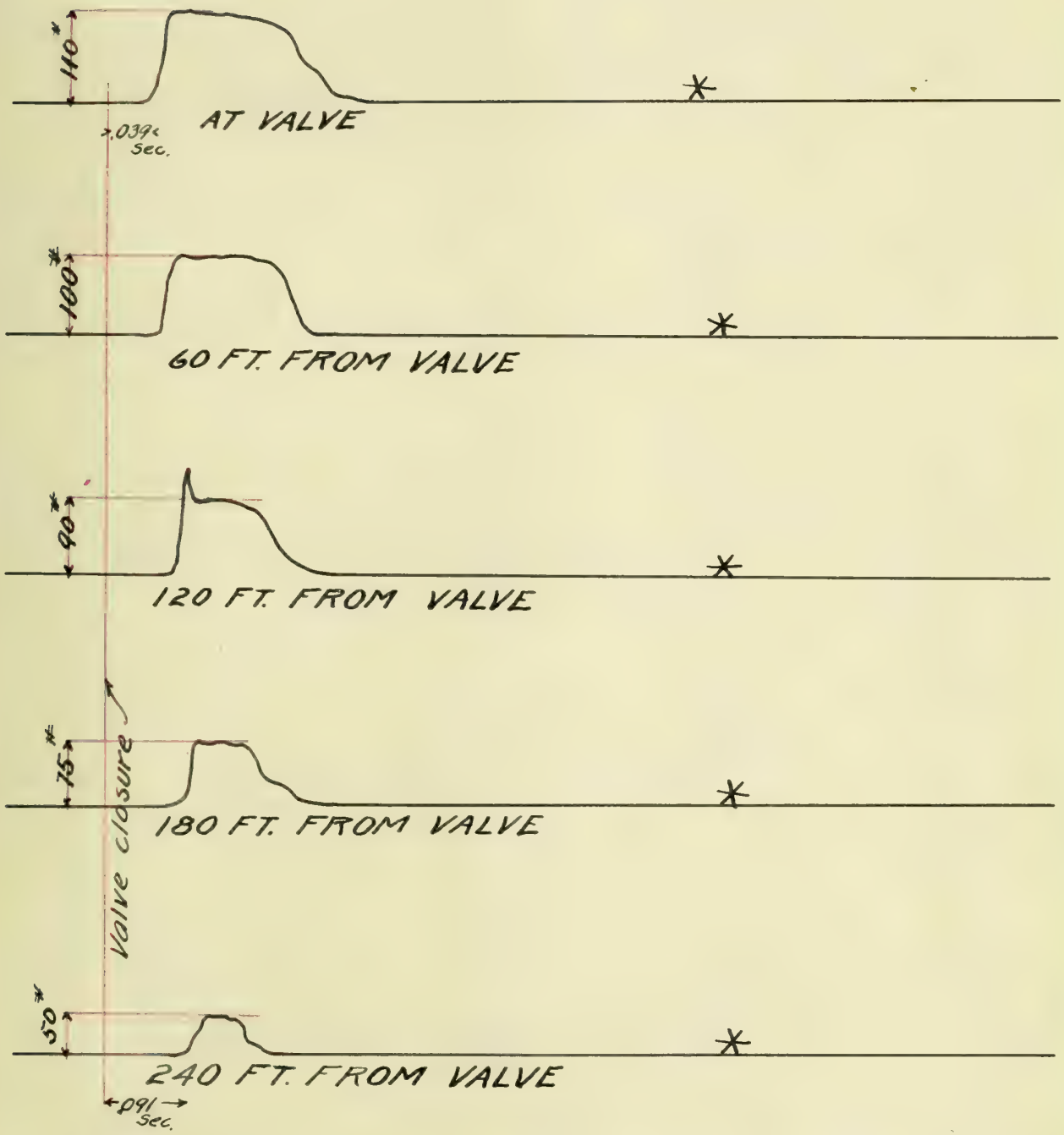
180 ft. Pipe V = 5.6 ft.

Pulsations	Pressures lbs. per sq. in.	Time between Pulsations in seconds
1	375	.63
2	150	.50
3	90	.42
4	30	

It will be noticed that the time between pulsations is less for each succeeding pulsation. An explanation of this can not now be given. It will also be noticed that the time between the first and second pulsations is proportional to the velocity of the water flowing in the pipe and proportional to the length of the pipe. The following diagrams on pages 33 to 39 show the general character of the indicator diagrams.

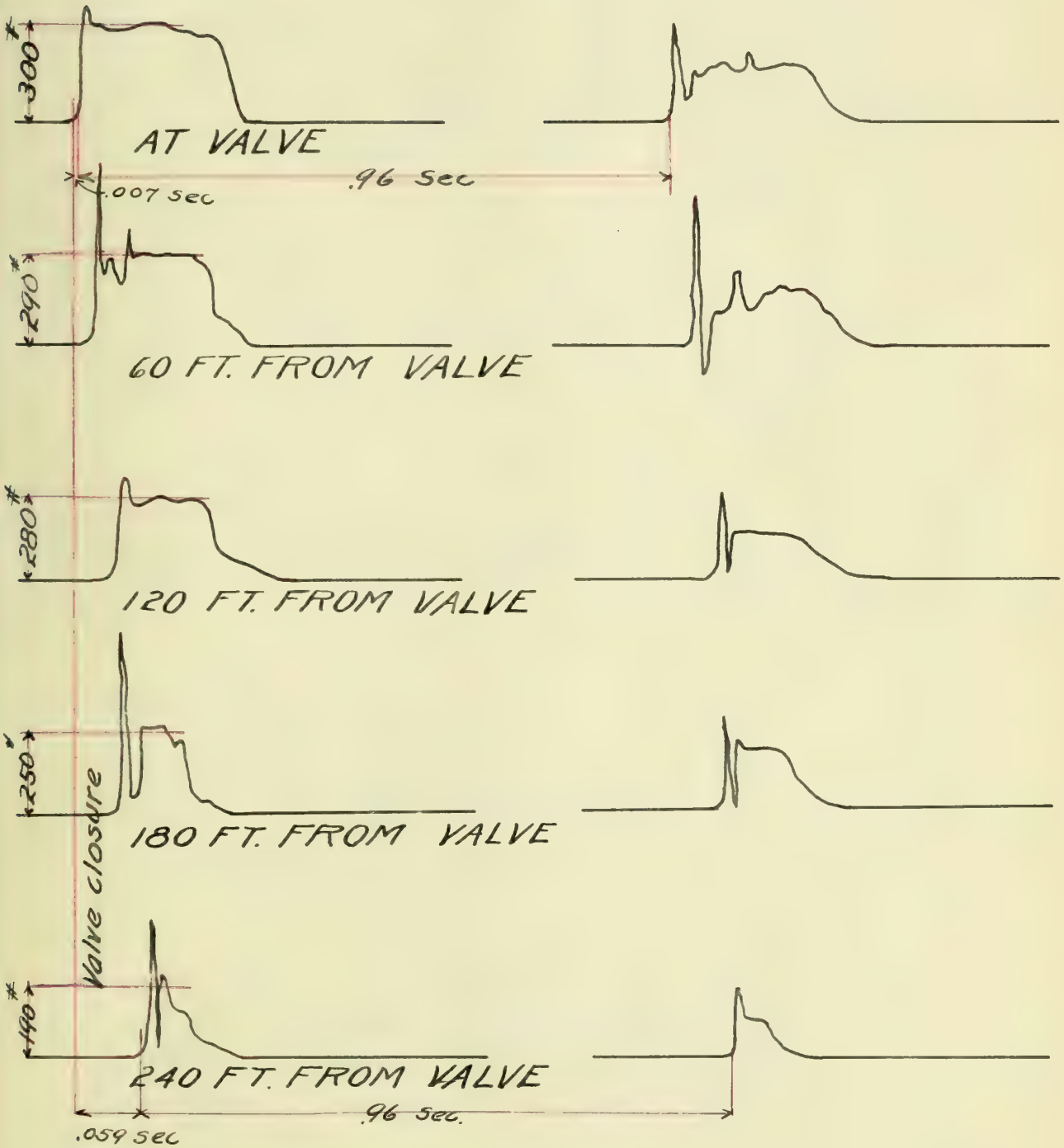
The scale of the diagrams does not show the true time between pulsations; the figures are correct rather than the scale.

DIAGRAM
SHOWING 1ST AND 2ND. PULSATIONS
300 FT PIPE
VELOCITY = 2.2 FT. PER SEC.



* SECOND PULSATION COULD NOT BE DISTINGUISHED

DIAGRAM
SHOWING 1ST. AND 2ND. PULSATIONS
300 FT. PIPE
VELOCITY = 5.4 FT. PER SEC.

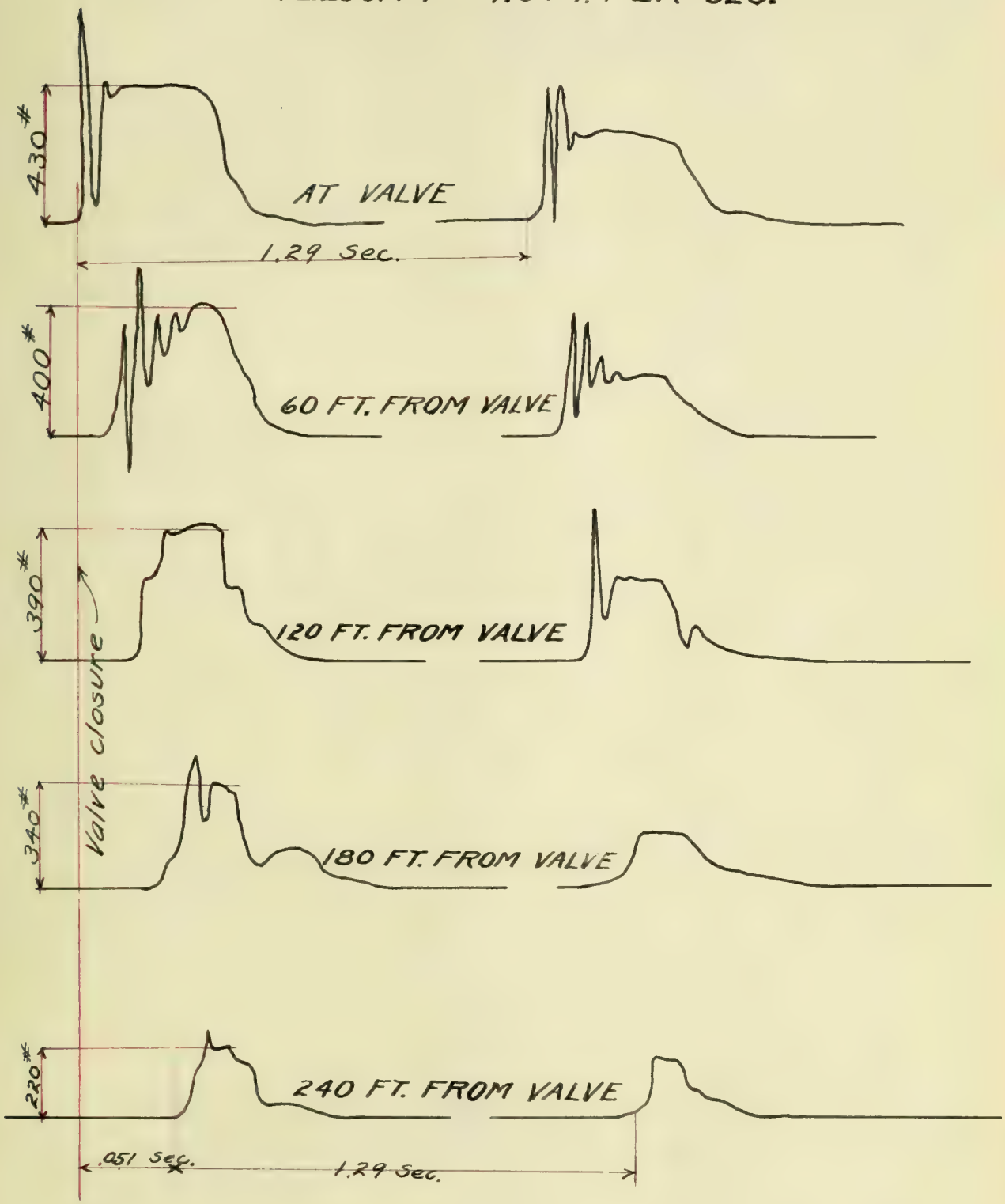


DIAGRAM

SHOWING 1ST. AND 2ND. PULSATIONS

300 FT. PIPE

VELOCITY = 7.0 FT. PER SEC.

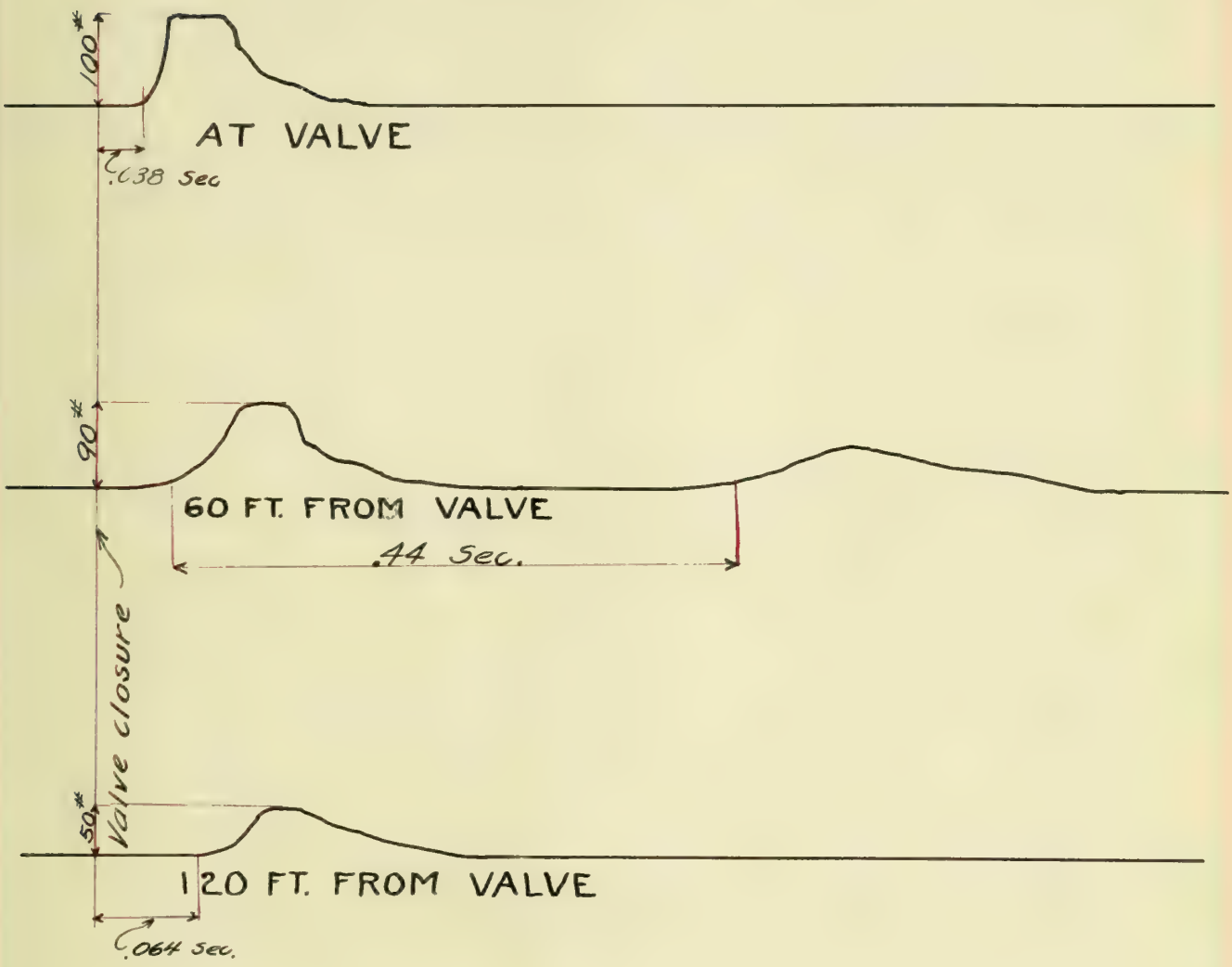


DIAGRAM

SHOWING 1ST AND 2ND PULSATIONS

180 FT. PIPE

VELOCITY = 2.2 FT. PER SEC.



NOTE – No second pulsation was observed at valve or 120 feet from valve

DIAGRAM

SHOWING 1ST. AND 2ND. PULSATIONS

180 FT. PIPE

VELOCITY = 5.6 FT. PER. SEC.

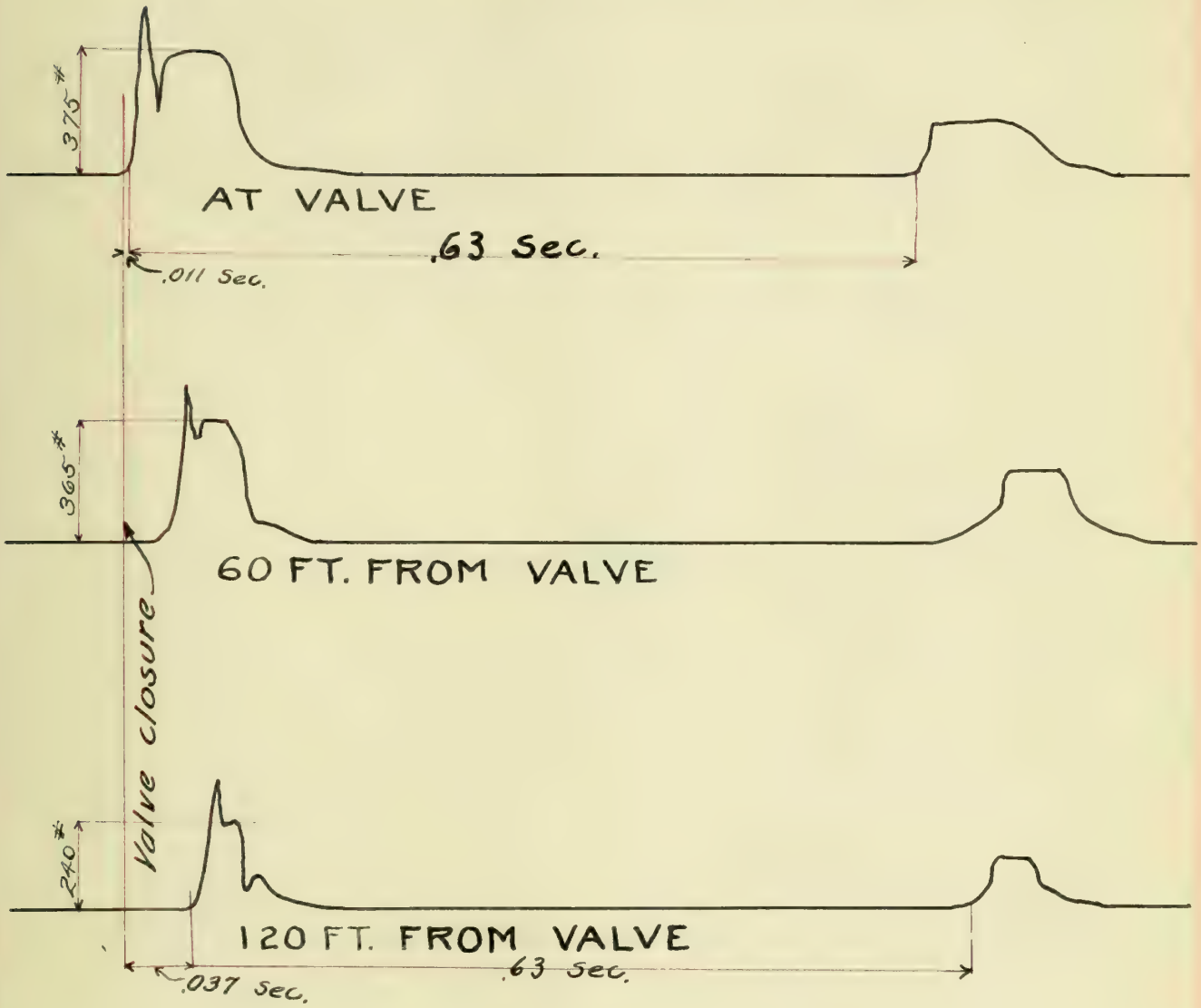
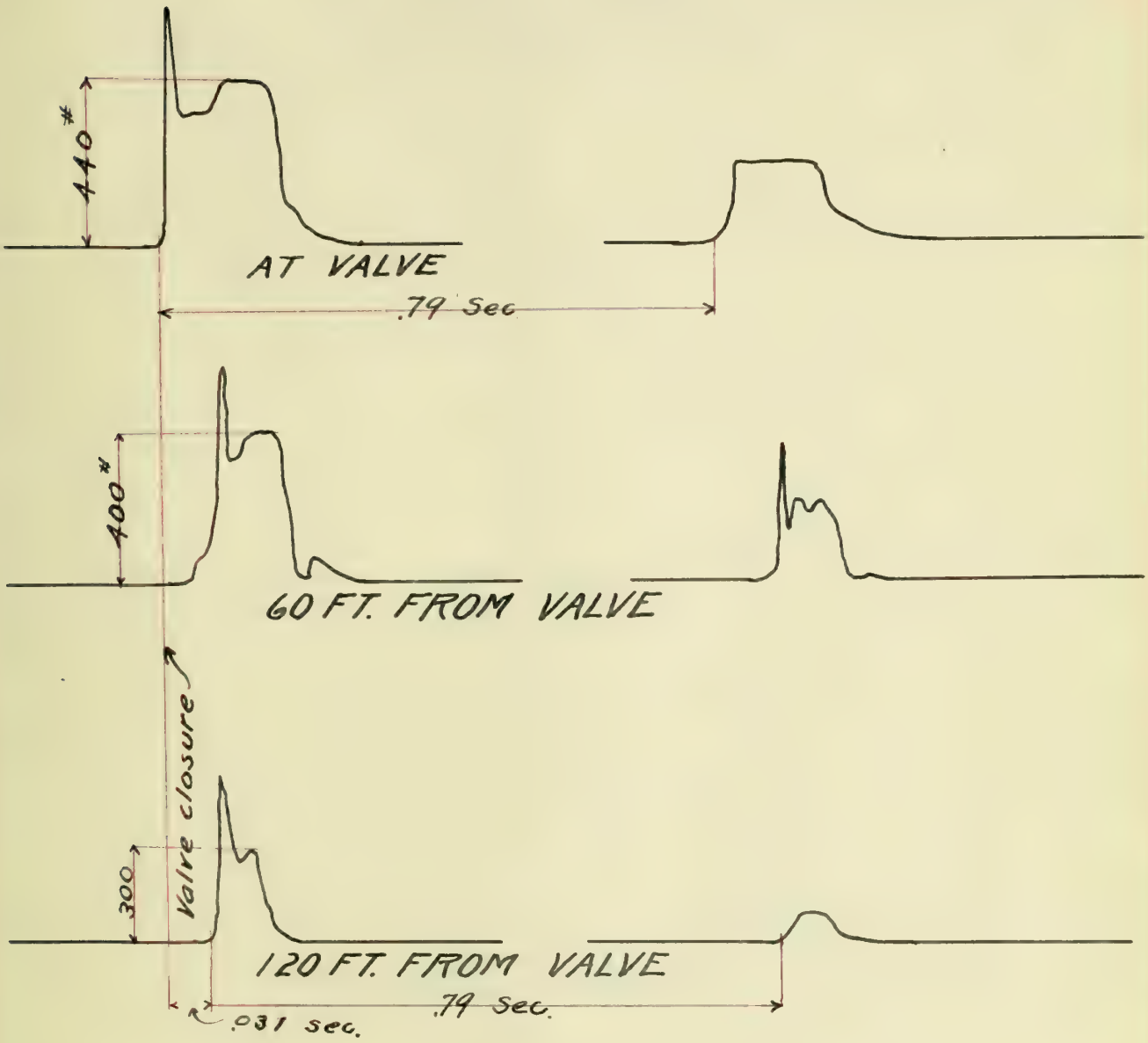


DIAGRAM
SHOWING 1ST AND 2ND PULSATIONS
180 FT. PIPE
VELOCITY = 7.7 FT. PER SEC.

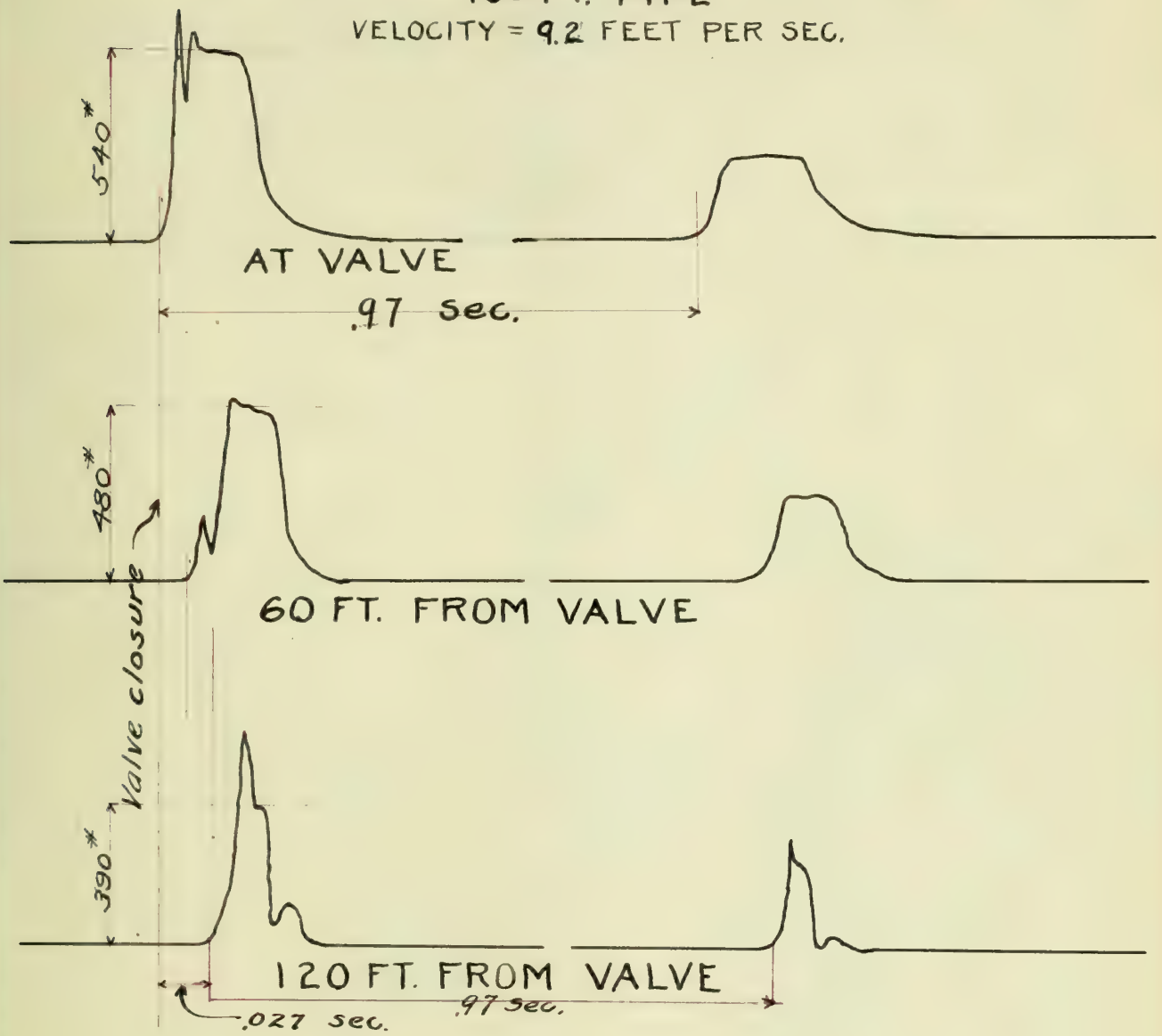


DIAGRAM

SHOWING 1ST. AND 2ND. PULSATIONS

180 FT. PIPE

VELOCITY = 9.2 FEET PER SEC.



Movement of the Water after the Valve is Closed

It is interesting to consider what takes place after the valve is closed. Let λ equal the amount of compression for a length X, then $\lambda = \frac{SX}{E}$ where S equals the unit pressure, and is equal to P, E the modulus of elasticity of the water. When $S = 100^{\#}$ and $E = 300000$, $\lambda = \frac{100 X}{300000} =$ the contraction in a column X long. For a column 20 feet long $\lambda = \frac{100 \times 12 \times 20}{300000} = .016$ inches, considering that the pressure is uniform for this distance. Taking the normal pressure for each 20 ft length of pipe diagram on pgl. 1 and 2 the approximate amount of compression for each 20 feet is found. Adding these amounts, beginning at the valve, the sum equals the total contraction of the column or the movement of the water at the free end after the valve is closed and up to the time of greatest compression when the water comes to a

standstill. This total movement divided by the velocity of the water in feet per second will give the time in which the water continues to flow into the pipe after the valve is closed, if we disregard the the time taken to generate the pressure at any point which the diagrams show to be very small. The time that the water flows after the valve is closed is shown in figures 1 and 2 plate 7. We should expect it to be the same as the time it takes the impulse to travel from the valve to the free end, but it is shown to be less. No explanation can here be given for this.

Tables showing the coincides with for different velocities and lengths of pipe are given on succeeding pages. The compression and the movement of the water are given in inches, and the time required for the impulse to travel and the time required for the water to flow as far as the calculated compression are given in seconds.

Calculated compression, movement and time

300 ft pipe V = 7.0 ft per sec.

Average Pressure	Dist. from Valve – feet	Compress'n in 20 ft.	Total Movem't	Time after impulse at Valve sec.	Movement / Velocity
400	0	0	0	0	0
399	20	.325	.326	.004	.0039
397	40	.324	.650	.008	.0078
395	60	.322	.972	.013	.0115
390	80	.318	1.290	.017	.0154
387	100	.316	1.606	.021	.0191
382	120	.312	1.918	.025	.0227
375	140	.306	2.224	.029	.0264
365	160	.298	2.522	.034	.0301
355	180	.289	2.811	.038	.0333
340	200	.277	3.088	.042	.0366
325	220	.265	3.353	.047	.0400
300	240	.245	3.598	.051	.0428
265	260	.216	3.814	.055	.0454
215	280	.175	3.989	.059	.0474
125	300	.102	4.091	.063	.0486

300 ft. Pipe V = 5.4 ft. Per Sec.

Average Pressure	Dist from Valve – feet	Comp. in 20 ft.	Total Movem't.	Time after impulse at Valve sec.	Movement / Velocity
305	0	.000	.000	.000	.000
303	20	.247	.247	.004	.0038
300	40	.245	.492	.008	.0076
295	60	.241	.733	.013	.0113
292	80	.238	.971	.017	.0150
288	100	.235	1.206	021	.0186
283	120	.231	1.437	.025	.0222
277	140	.226	1.663	.029	.0256
270	160	.220	1.883	.034	.0290
260	180	.212	2.095	.038	.0323
245	200	.200	2.295	.042	.0354
230	220	.188	2.483	.047	.0383
205	240	.167	2.650	.051	.0410
177	260	.144	2.794	.055	.0430
137	280	112	2.906	.054	.0450
70	300	.057	2.963	.063	.0457

300 ft. Pipe V = 2.2 ft. per sec

Average Pressure	Dist. from valve ft.	Compress'n in 20 ft.	Total Movement	Time after impulse at valve	Movement Velocity
110	0	.000	.000	.000	0
108	20	.0880	.0880	.004	.0033
105	40	.0855	.1735	.008	.0066
103	60	.0840	.2575	.013	.0097
100	80	.0816	.3391	.017	.0129
97	100	.0790	.4181	.021	.0158
95	120	.0775	.4956	.025	.0188
92	140	.0750	.5906	.029	.0225
87	160	.0710	.6616	.034	.0250
81	180	.0660	.7276	.038	.0275
75	200	.0610	.7886	.042	.0298
66	220	.0538	.8424	.047	.0319
57	240	.0465	.8889	.051	.0336
45	260	.0368	.9257	.055	.0350
33	280	.0270	.9527	.059	.0361
15	300	.0122	.9649	.063	.0365

180 ft. Pipe V = 9.2 ft. per sec.

Average Pressure	Dist. from valve ft.	Compress'n in 20 ft.	Total Movement	Time after impulse at valve	Movement Velocity
525	0	0	0	0	0
520	20	.424	.424	.004	.0036
507	40	.417	.841	.008	.0075
488	60	.399	1.240	.013	.0113
460	80	.375	1.615	.017	.0147
425	100	.346	1.961	.021	.0179
385	120	.313	2.274	.025	.0206
325	140	.265	2.539	.029	.0234
255	160	.207	2.746	.034	.0249
150	180	122	2.868	038	.0262

180 ft Pipe V = 7.7 ft. per sec.

Average Pressure	Dist. from Valve ft.	Compres'n in 20 ft.	Total Movement	Time after impulse at valve sec	Movement / Velocity
440	0	0	0	0	0
435	20	.335	.335	.004	.0038
423	40	.345	.700	.008	.0076
407	60	.332	1.032	.013	.0112
390	80	.328	1.360	.017	.0147
360	100	.294	1.654	.021	.0178
327	120	.267	1.921	.025	.0204
273	140	.223	2.144	.029	.0231
210	160	.171	2.315	.034	.0250
112	180	.091	2.406	.038	.0260

180 ft. Pipe V = 5.6 ft. per sec.

Average Pressure	Dist. from Valve - ft	Compres'n in 20 ft	Total Movement	Time after impulse at valve	Movement / Velocity
322	0	0	0	0	0
320	20	.260	.260	.004	.0039
310	40	.252	.512	.008	.0076
300	60	.244	.756	.013	.0112
283	80	.230	.986	.017	.0147
262	100	.212	1.198	.021	.0178
235	120	.191	1.389	.025	.0204
187	140	.152	1.541	.029	.0230
130	160	.105	1.646	.034	.0245
70	180	.057	1.703	.038	.0253

180 ft Pipe. V = 2.2 ft Per Sec

Average Pressure	Dist. from Valve ft.	Compres'n in 20 ft.	Total Movement	Time after impulse at valve	Movement / Velocity
100	0	0	0	0	0
97	20	.079	.079	.004	.0030
90	40	.073	.152	.008	.0058
82	60	.067	.219	.013	.0083
75	80	.061	.280	.017	.0106
67	100	.055	.335	.021	.0127
60	120	.049	.384	.025	.0145
48	140	.039	.423	.029	.0160
33	160	.027	.450	.034	.0170
22	180	.018	.468	.038	.0178

PLATE 7

Straight line represents time required for impulse to travel along the pipe

Curved lines represent time required for water to flow a distance equal to calculated compression

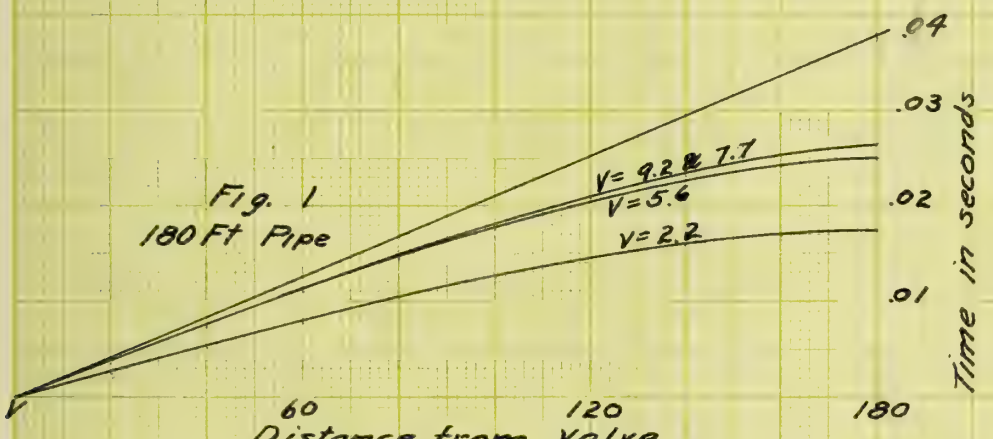


Fig. 1
180 Ft Pipe

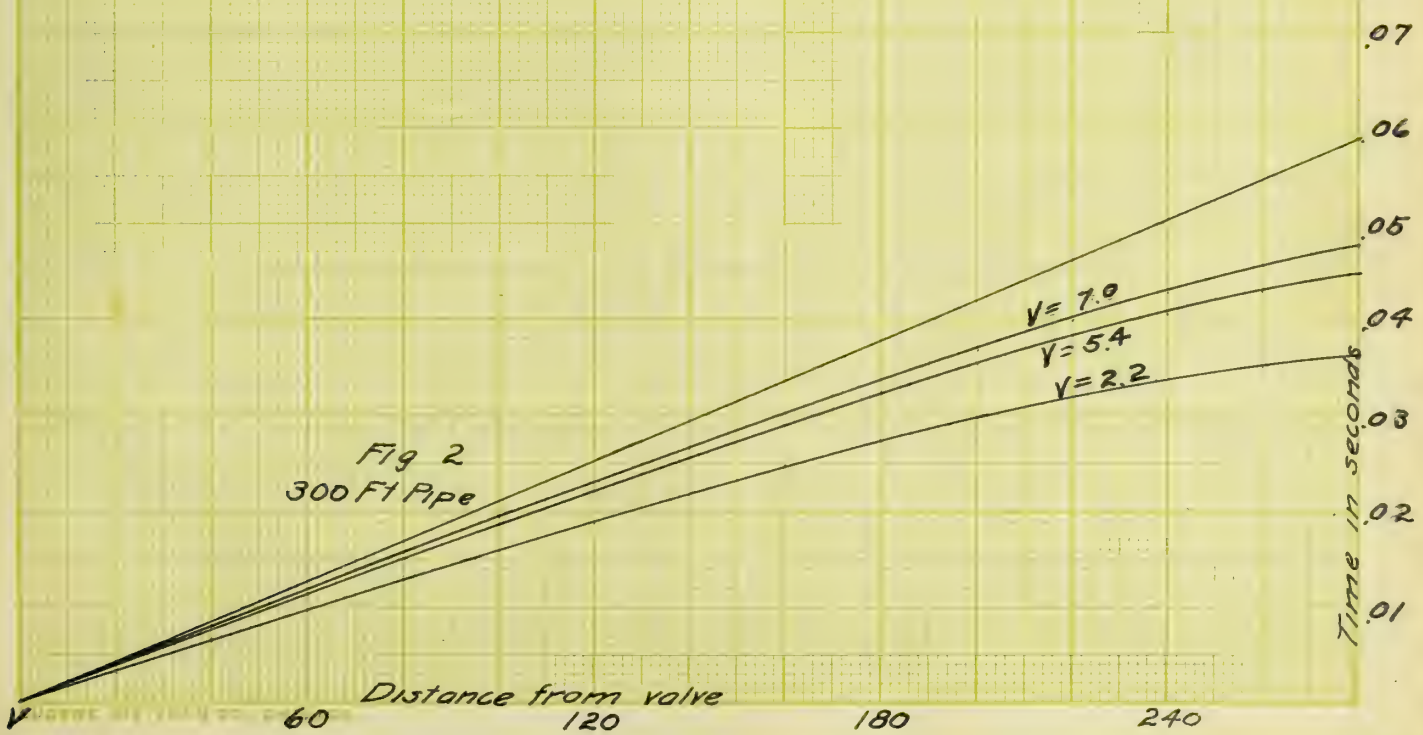


Fig 2
300 Ft Pipe

Summary

In all the experiments by the writer and in experiments by others it was found that the pressure created by the sudden closing of the valve is nearly proportional to the velocity of the water flowing in the pipe. It seems to be somewhat less for low velocities.

The pressure is greatest at the valve and zero at the free end. It decreases not as the distance from the valve increases but nearly as the square root of the distance; the function was not found. The reason for this decrease in pressure is as yet unknown.

The pressure is not one shock but several successive shocks at decreasing intervals, the time of these intervals increasing as the length of the pipe and as the velocity of the water.

The pressure does not occur simultaneously at all points along the pipe,

but it is felt first at the valve and this impulse travels along the pipe with a velocity of 4600 feet per second.

The time that the compression lasts at any point is the time it takes the impulse to travel from that point to the free end and return to the point in question.

The computed time that the water continues to flow into the pipe after the valve is closed is not the same as the time it takes the impulse to travel from the valve to the free end. The reason for this is not known.

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